

**EVALUATE THE IMPACT OF PARTICLES SIZE DISTRIBUTION ON  
FRICTION FACTOR AND PRESSURE DROP FOR FLOW THROUGH  
PACKED BED**

**By**

**FAUZI AHMED OMAR**



**- LIBRARY -  
INFRASTRUCTURE UNIVERSITY  
KUALA LUMPUR**

**Thesis submitted in partial fulfilment as the degree requirement for the  
Master of Science in Water Resources in the Faculty of Engineering  
And Technology Infrastructure**

**IUKL**

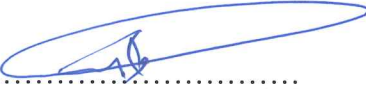
**2016**

## DECLARATION

I do hereby solemnly declare that the above titled thesis submitted by me is partial fulfilment of the degree program enumerated above that:

1. This thesis is my original work, except where otherwise acknowledged in the text;
2. This work has not been published earlier; and
3. This thesis shall not be submitted further by me in future for obtaining any degree from this or another university/institution.

Name: FAUZI AHMED OMAR

Signature: 

Date: 2015/1/2016

## Approval

We have examined this manuscript and verify that it meets the programme and University requirement for the degree of Master of Science in Water Resources.

Name of Supervisor: Assoc.Prof .Dr. Manal Mohsen Abood

Name of Faculty: Faculty of Engineering and Technology Infrastructure  
IUKL

Name of Internal Examiner: Dr. Mohd Sofiyan Sulaiman

Name of Faculty: Faculty of Engineering and Technology Infrastructure  
IUKL

Name of Internal Examiner: Azlinda Saadon

Name of Faculty: Faculty of Engineering and Technology Infrastructure  
IUKL

Name of Director of CPS: Kamaljeet Kaur

Centre for Postgraduate Studies

IUKL

Date: /23/5/ 2016

  
**KAMALJEET KAUR**  
Director  
Centre for Postgraduate Studies  
Infrastructure University Kuala Lumpur

## ACKNOWLEDGMENT

Alhamdulillah, all praise to Allah (SWT) for giving me the strength, determination and perseverance to complete this thesis. No one in this world walks through life in solitude. During my life journey there have been many individuals that influenced my plan of action and my commitment to obtain a higher education degree. To those significant individuals I will be eternally grateful for this inspiration. The work in this thesis has been an inspiring and sometimes challenging but an interesting experience. It has been made possible by many other people, who have supported and guided me.

Firstly, extraordinary appreciation is extended to my supervisor, very distinguished academic fellow **Associate Professor Dr. Manal Mohsen Abood** without her effort this thesis would not have been completed. Not only she helped me on my dissertation, but also encouraged and trained me to be a good researcher.

I am also indebted to my parents, who always support me in whatever I pursued, in all the ups and downs of life and guide me in the good and in the bad. All those lessons that they gave me throughout my life were extremely helpful and useful. Their continuous love and blessing, and constant prayers made this journey possible. Finally, I thank the rest of my family members, especially to my siblings and friends who always believed in me and motivated me to accomplish this goal.

## ABSTRACT

This study has presented the flow of the water over packed bed which contains glass particles of spherical uniform shaped, 9.34, 13.30 and 23mm size and in the second phase of the study mix material of Marble, 5mm, Gravel 7.5mm, Acrylic ball 8.52mm and spherical glass size of 9.34 were mixed and used as a packing material. The flow of water was controlled using a regulator, initial and final pressure was recorded with pressure meter in packed beds. The findings of the study indicated that pressure drop increases using narrow size uniform shaped spherical glass particles while lower pressure drop has been seen with bigger size uniform shaped spherical glass particles. Moreover, in the case of mix material has higher pressure drop due to the irregular shape of the material and narrow size of the particles. The other variable of the study is friction factor, Reynolds Number and porosity of the material. The findings indicated higher Reynolds number is obtained for smaller particle size such as 9.34mm spherical glass shown higher Reynolds number compare to 13.30mm and 23.0 mm spherical bigger size particles. Additionally, the study concluded that the Reynolds number is not a linear function to friction factor. Lastly, higher porosity of the material is resulted higher pressure drop. In the recommendations, uniform shape, bigger size particles found more favourable to reduce pressure drop in packed beds.

## Table of Contents

Title page.....	i
Declaration.....	ii
Approval Page.....	iii
Acknowledgment.....	iv
Abstract.....	v
Table of Contents.....	vi
List of Figures.....	ix
List of Table.....	xii
List of Abbreviations.....	xiii

### CHAPTER 1: INTRODUCTION

1.1 Introduction.....	1
1.2 Problem Statement.....	3
1.3 Aim of the Study.....	4
1.4 Objectives of the Study.....	4
1.5 Scope of the Study.....	5
1.6 Significance of the Study.....	5
1.7 Thesis organization.....	6

### CHAPTER 2: LITERATURE REVIEW

2.1 Introduction.....	7
2.2 Packed Bed.....	8
2.3 Ergun' Equation.....	8
2.4 Impact of Particles distribution and Packed Bed structure.....	13
2.5 Impact of Particles size, and distribution on packed bed.....	15
2.6 Effect of particle Diameter on Pressure Drop.....	19
2.7 Effect of Porosity on Pressure Drop.....	19
2.8 Packed Bed of Spheres.....	20
2.9 Influence of Particle Roughness for Pressure drop of Packed Bed.....	21
2.10 Correlation for the Pressure Drop Calculation.....	22

2.11 Density of Packed Bed Particles.....	24
2.12 Relationship between Friction Factor and Reynolds Number for Flow through Packed Beds.....	25
2.13 Packed Beds of Various Particle Shapes.....	27
2.14 Porosity equation for water flow through porous media of packed bed.....	31
2.15 Description of the apparatus used for packed bed.....	33

**CHAPTER 3: RESEARCH METHODOLOGY**

3.1 Introduction.....	36
3.2 Materials and equipments.....	36
3.2.1 Packed bed.....	36
3.2.2 Pressure Pump Selected .....	37
3.3 Particles Materials.....	38
3.4 Spherical Glass .....	38
3.5 Mix Materials.....	39
3.6 Study Flow Chart.....	42
3.7 True density packing material .....	43
3.8 Experimental Setup.....	44
3.9 Statistical Analysis.....	47
3.10 Experimental Procedure.....	48

**CHAPTER 4: RESULTS ANALYSIS AND DISCUSSION**

4.1 Introduction.....	51
4.2 True density .....	51
4.3 Pressure Drop Verse Velocity of Spherical Glass Material.....	52
4.4 Pressure Drop Verse Velocity of Mix Materials (Unsorted).....	55
4.5 Simulation and prediction comparative.....	58
4.6 Friction Factor and Reynolds Number of Spherical Glass Materials.....	62
4.7 Friction Factor and Reynolds Number of Unsorted.....	65
4.8 Experimental Work Results and cooperation with others.....	67

**CHAPTER 5: CONCLUSION AND DISCUSSION**

5.1 Conclusion.....68  
5.2 Recommendations.....70  
Reference.....71  
Appendix ..... 76



## LIST OF FIGURE

Figure No.	Title of Figure	Page No.
1.1	Typical Packed bed diagram	2
2.1	Pressure drop through section 1 of the random packing with standard deviation error bars.	14
2.2	Pressure drop through section 1 of the structured packing with standard deviation error bars.	14
2.3	Graphical description of the Simple Cubic (SC), Body-centered Cubic (BCC) and the Face-centered Cubic (FCC) unit cells.	21
2.4	Friction Factor versus Reynolds Number	26
2.5	Basic Geometries used in mean voidage measurements	28
2.6	Mean Voidage in packed beds of spherical particles	29
2.7	Mean Voidage in packed beds of solid cylindrical particles	29
2.8	Mean Voidage in packed beds of hollow cylindrical particles.	30
2.9	Mean Voidage in packed beds of 4-hole cylindrical particles.	30
2.10	Indicates increase in the particle diameter and increase in the bed porosity.	34
2.11	Porosity versus particle	35
3.1	Packed bed filled with spherical glass material	37
3.2	Pressure pump Selected	38
3.3	Spherical Glass	39
3.4	Marble	39
3.5	Acrylic balls	40
3.6	Carvel	40
3.7	Spherical Glass	41
3.8	Study Flow Chat	42
3.9	True density Test	43

3.10	Schematic diagram of packed bed	44
3.11	Packed Bed	45
3.12	Inlet and outlet pressure meter	46
3.13	Velocity meter of packed bed	46
4.1	Pressure drops versus velocity (spherical Glass particles) of diameters 9.34 mm, bed porosity of 0.95 packing height of 44cm, and bed diameter of 8 cm.	54
4.2	Pressure drops versus velocity for Pea Glass of diameters 13.30 mm, bed porosity of 0.987 packing height of 44cm, and bed diameter of 8 cm.	56
4.3	Pressure drops versus velocity for Pea Glass of diameters 23 mm, bed porosity of 0.989 packing height of 44cm, and bed diameter of 8 cm.	57
4.4	Pressure drops versus velocity for unsorted mix material dia range between 2mm to 17mm and bed porosity of 0.951 packing height of 44cm, and bed diameter of 8.	57
4.5	Simulation and Prediction Pressure drops versus velocity (spherical Glass particles) of diameters 9.34 mm, bed porosity of 0.95 packing height of 44cm, and bed diameter of 8 cm.	59
4.6	Simulation and Prediction Pressure drops versus velocity for Pea Glass of diameters 13.30 mm, bed porosity of 0.987 packing height of 44cm, and bed diameter of 8 cm.	59
4.7	Simulation and Prediction Pressure drops versus velocity for Pea Glass of diameters 23 mm, bed porosity of 0.989 packing height of 44cm, and bed diameter of 8 cm.	60
4.8	Simulation and Prediction Pressure drops versus velocity for unsorted mix material dia range between 2mm to 17mm and bed porosity of 0.951 packing height of 44cm, and bed diameter of 8.	61
4.9	Friction factor versus Reynolds numbers for particles diameter of 9.34mm and porosity of 0.955.	64
4.10	Friction factor versus Reynolds numbers for particles diameter of 13.30mm and porosity of 0.978.	64
4.11	Friction factor versus Reynolds numbers for particles diameter of 23mm and porosity of 0.989	65

4.12 Friction factor versus Reynolds numbers for Pea mix materials Marble, Acrylic balls, Gravel, glass Spheres of particles diameter of and porosity of 0.951

## LIST OF TABLE

Table No.	Title of Table	Page No.
2.1	Experimental test sections	20
2.2	The True Densities of Particles	26
2.3	Physical Characteristics of employed particles	28
2.4	Mean voidage correlations developed	31
2.5	Experimental data for different types and sizes of packing	33
4.1	True densities of the Spherical Glass particles	52
4.2	Pressure drop versus Velocity (Spherical Glass particles size 9.34, 13.30, 23).	54
4.3	Mix material Pressure drop versus Velocity	56
4.4	Prediction Pressure drop versus Velocity (Spherical Glass particles size 9.34, 13.30, 23 and Unsorted).	58
4.5	Simulation Pressure drop versus Velocity (Spherical Glass particles size 9.34, 13.30, 23 and Unsorted).	60
4.6	Performance statistics of the comparison Simulation and Prediction (Simulation Vs. Prediction).	61
4.7	Velocity verses Reynolds Number of spherical particles	63
4.8	Friction verses Velocity of spherical particles	63
4.9	Reynolds number of mix materials	66
4.10	Formula for friction factor Vs Reynolds number	67

## LIST OF ABBREVIATIONS

Abbreviation	Description
$\Delta P$	Pressure drop through packed bed, Pa ( $\text{kg/m}\cdot\text{s}^2$ ).
L	The height of packing in the bed (m).
$D_p$	Spherical diameter
M	Dynamic viscosity of the fluid
$\epsilon$	Void fraction
$\Phi$	Sphericity.
D	the particle size
$A_p$	Area of the particle
E	Porosity of the bed.
P	Density of fluid ( $\text{kg/m}^3$ ).
$\rho_p$	Density of particle ( $\text{kg/m}^3$ ).
$\rho_b$	Bulk density ( $\text{g/cm}^3$ ).
$\rho_t$	True density ( $\text{g/cm}^3$ ).
V	Superficial Velocity (m/s)
Q	the volumetric flow rate of fluid ( $\text{m}^3/\text{sec}$ )
A	the packed bed cross sectional area ( $\text{m}^2$ )
$V_0$	Volumetric flow rate
$f_p$	friction factor
$Re$	Reynolds Number
dP	Diameter of the particle (m)
P	water density
$\rho_w$	density of water at laboratory temperature, ( $\text{g/cm}^3$ )
$w_1$	weight of the particles, (g)
$w_2$	weight of cylinder filled with water, (g)
$w_3$	weight of cylinder with water and particles, (g)
U	Fluid velocity
$\rho$	Fluid density

## CHAPTER 1

### INTRODUCTION

#### 1.1 Introduction

A packed bed, in chemical processing, is a pipe, hollow tube, or any other vessel that is filled with a packing material. It might be randomly filled of small objects like Raschig rings otherwise it could be a precisely packing of a designed structure. Packed beds could also have adsorbents or catalyst particles like granular activated carbon, zeolite pellets, etc. Normally, the purpose of a packed bed is in order to improve contact between two phases in a chemical process or any other process. Packed beds can be used in a distillation process, a scrubber, or a chemical reactor, but packed beds were also used to store heat in chemical plants.

Generally, Newtonian fluid flow through packed bed obeys Darcy's law at low Reynolds number and packed bed is considered porous (Luckos & Bunt, 2011). The major application of packed bed has seen in chemical, metallurgical, nuclear and other process engineering industries. The utilization of packed bed in the industries is a catalytic reactor, drying, adsorption of a solute, wastewater treatment, gas absorption combustion, filter bed, and the crude oil flow in the reservoir of the petroleum (Zainab, 2010). A conventional packed bed is a tube of cylindrical shape which is filled with various shape and size packing materials. Figure 1.1 shows the commonly use packed bed tube;

## Reference

- Abbas, M. N. (2011). Modeling Of Porosity Equation For Water Flow Through Packed Bed Of Monosize Spherical Packing. *Journal Of Engineering And Development*, 15(4).
- Abdzaid, Z. T. (2012). Investigation of the friction factor\_ Reynolds number relationship for flow through packed bed: Al-Mustansiryiah University/College of Enginnering.
- Al-Sharify, T., Al-Sharify, Z., & Abass, M. (2009). Modification of porosity equation for water flow through porous media. *Journal of Environmental Studies*, 2, 65-72.
- Allen, K., Von Backström, T., & Kröger, D. (2013). Packed bed pressure drop dependence on particle shape, size distribution, packing arrangement and roughness. *Powder Technology*, 246, 590-600.
- Al-Dulami B.(1998). Porosity of Particle mixture using RRSB size distribution , M.SC.Thesis, Al- Nahrain Univerity,1998.
- Andrei Koekemoer, A. L. (2015). Fuel. *Effect of material type and Particle Size distribution on pressure drop in packed beds of large particles: Extending the Ergun equation.*
- Abbass M.N. (2009). Estimated equations for water flow through packed bed of multi – size particles. *Al-Qadisiya Journal For Engineering Sciences* Vol. 2 No.4
- Backhurst, J. R., Harker, J. H., & Richardson, J. (2002). *Solutions to the Problems in Chemical Engineering Volume 2 and Volume 3*: Butterworth Heinemann.
- Barnard, F. C. (2011). *Influence of structuredness on the pressure drop through a packed pebble bed*, North-West University.
- Basu, S., Dixon, C., Fereday, C., Muehe, A., Perry, T., & Sides, I. C. (2003). Comparison of the Ergun Equation with Experimental Values Regarding Pressure Drop and Fluid Velocity. *Article given on the internet at the web site: [http://rothfus.cheme.cmu.edu/tlab/p\\_beds/projects/t2\\_s03/t2\\_s03.pdf](http://rothfus.cheme.cmu.edu/tlab/p_beds/projects/t2_s03/t2_s03.pdf).*
- Beithou, N., Albayrak, K., & Abdulmajeed, A. (1998). Effects of porosity on the free convection flow of non-Newtonian fluids along a vertical plate embedded in a porous medimum. *Tr,J Engg .Env.Sci*, 22,203-209.

- Benyahia, F., & O'Neill, K. (2005). Enhanced voidage correlations for packed beds of various particle shapes and sizes. *Particulate science and technology*, 23(2), 169-177.
- Benyahia, F., & O'Neill, K. E. (2005). Enhanced voidage correlations for packed beds of various particle shapes and sizes *Particulate Science and Technology*: Taylor & Francis Inc.
- Bey, O., & Eigenberger, G. (1997). Fluid flow through catalyst filled tubes. *Chemical Engineering Science*, 52(8), 1365-1376.
- Bu, S., Yang, J., Zhou, M., Li, S., Wang, Q., & Guo, Z. (2014). On contact point modifications for forced convective heat transfer analysis in a structured packed bed of spheres. *Nuclear Engineering and Design*, 270, 21-33.
- Cheng, N.-S. (2011). Wall effect on pressure drop in packed beds. *Powder Technology*, 210(3), 261-266.
- Chhabra, R. P. (2007). *Bubbles, Drops and Particles in Non - Newtonian Fluids*. Kanpur: Taylor & Francis.
- Choi, Y. S., Kim, S. J., & Kim, D. (2008). A semi-empirical correlation for pressure drop in packed beds of spherical particles. *Transport in porous media*, 75(2), 133-149.
- Chung, P., Koontz, R., & Newton, B. (2002). Packed Beds: Pressure Drop versus Fluid Velocity and the Ergun Equation. Article given on the internet at the web site: [http://rothfus.cheme.cmu.edu/tlab/p\\_beds/projects/t10\\_s02/t10\\_s02.pdf](http://rothfus.cheme.cmu.edu/tlab/p_beds/projects/t10_s02/t10_s02.pdf).
- Comiti, J., & Renaud, M. (1989). A new model for determining mean structure parameters of fixed beds from pressure drop measurements: application to beds packed with parallelepipedal particles. *Chemical Engineering Science*, 44(7), 1539-1545.
- Crawford, C., & Plumb, O. (1986). The influence of surface roughness on resistance to flow through packed beds. *Journal of fluids engineering*, 108(3), 343-347.
- Cumberland, D., & Crawford, R. J. (1987). The packing of particles.
- Di Felice, R., & Gibilaro, L. (2004). Wall effects for the pressure drop in fixed beds. *Chemical Engineering Science*, 59(14), 3037-3040.



- Dullien, F., El-Sayed, M., & Batra, V. (1977). Rate of capillary rise in porous media with nonuniform pores. *Journal of Colloid and Interface Science*, 60(3), 497-506.
- Eisfeld, B., & Schnitzlein, K. (2001). The influence of confining walls on the pressure drop in packed beds. *Chemical Engineering Science*, 56(14), 4321-4329.
- Erdim, E., Akgiray, Ö., & Demir, İ. (2015). A revisit of pressure drop-flow rate correlations for packed beds of spheres. *Powder Technology*, 283, 488-504.
- Edison A. and Kim J. (2006). Correlation of Pressure Drop and Flow Rate Using Packed Beds. *Carnegie Mellon University, Chemical Engineering Department (2006)*
- Ergun, S. (1952). Fluid flow through packed columns. *Chemical engineering progress*, 48.
- Ergun, S. (1953). Pressure drop in blast furnace and in Cupola. *Industrial & Engineering Chemistry*, 45(2), 477-485.
- Foust, A., Wenzel, L., Clump, C., Maus, L., & Andersen, L. (1980). Principles of Unit Operations. John Wiley & Sons. New YORK, NY
- Geankoplis, C. (2003). *Transport processes and separation process principles (includes unit operations)*: Prentice Hall Press.
- Greeff, S., Slaghuis, J., & Van der Walt, T. (1998). *Permeability of packed coal beds: The effect of particle size distribution, particle size and coal type*.
- Hayes, R., Afacan, A., & Boulanger, B. (1995). An equation of motion for an incompressible Newtonian fluid in a packed bed. *Transport in porous media*, 18(2), 185-198.
- Hellström, J., & Lundström, T. (2006). *Flow through porous media at moderate Reynolds number*. Paper presented at the International Scientific Colloquium: Modelling for Material Processing.
- Hjertager, B. H., Solberg, T., & Hansen, K. G. (2007). Reactive gas solids flow in circulating fluidised beds. *Progress in Computational Fluid Dynamics, an International Journal*, 7(2-4), 139-151.

- Kishore, N., Chhabra, R., & Eswaran, V. (2007). Mass transfer from a single fluid sphere to power-law liquids at moderate Reynolds numbers. *Chemical Engineering Science*, 62(21), 6040-6053.
- Koekemoer, A., & Luckos, A. (2015). Effect of material type and particle size distribution on pressure drop in packed beds of large particles: Extending the Ergun equation. *Fuel*.
- Kunii, D., & Levenspiel, O. (2013). *Fluidization engineering*: Elsevier.
- Kunii D, L. O. (1991). *Fluidization Engineering*. Boston: Butterworth Heinemann.
- Leva, M. (1951). Elutriation of fines from fluidized systems. *Chemical Engineering Progress*, 47(1), 39-45
- Leva, M. (1959). *Fluidization*: McGraw-Hill.
- Luckos, A., & Bunt, J. R. (2011). Pressure-drop predictions in a fixed-bed coal gasifier. *Fuel*, 90(3), 917-921.
- McCabe, W., Smith, J., & Harriott, P. (2005). Leaching and Extraction. *Unit Operations of Chemical Engineering*, 764.
- Mehta, D., & Hawley, M. (1969). Wall effect in packed columns. *Industrial & Engineering Chemistry Process Design and Development*, 8(2), 280-282.
- Montillet, A. s. (2004). Flow through a finite packed bed of spheres: a note on the limit of applicability of the Forchheimer-type equation. *Journal of fluids engineering*, 126(1), 139-143.
- Moreira, E., & Coury, J. (2004). The influence of structural parameters on the permeability of ceramic foams. *Brazilian Journal of Chemical Engineering*, 21(1), 23-33.
- Motil, B. J., Nahra, H. K., & Balakotaiah, V. (2005). Hydrodynamics of packed bed reactor in low gravity: SAE Technical Paper.
- Niven, R. K. (2002). Physical Insight in to the Ergun and Wen and Yu equations for fluid flow in packed and fluidised beds. *Che Eng Sci*.

- Niven, R. K. (2002). Physical insight into the Ergun and Wen & Yu equations for fluid flow in packed and fluidised beds. *Chemical Engineering Science*, 57(3), 527-534.
- Nagam O. K.(2010). Estimated Equations for Water Flow Through Packed Bed of Mono Size Spherical Packing System. *Iraqi Journal of Civil Engineering* Vol. 6, No. 3, pp. 60-69.
- Singh, R., Saini, R., & Saini, J. (2006). Nusselt number and friction factor correlations for packed bed solar energy storage system having large sized elements of different shapes. *Solar Energy*, 80(7), 760-771.
- Sutera S.P., S. R. (1993). *The History of Poiseuilles Law*. Paper presented at the Annual Review of Fluid Mechanics.
- Wentz, C. A., & Thodos, G. (1963). Total and form drag friction factors for the turbulent flow of air through packed and distended beds of spheres. *AIChE Journal*, 9(3), 358-361.
- Wu, J., Yu, B., & Yun, M. (2008). A resistance model for flow through porous media. *Transport in porous media*, 71(3), 331-343.
- Yang, W. C. (2003). *Handbook of Fluidization and Fluid Particle Systems*. New York: Marcel Dekker.
- Zainab T A. (2010). Investigation of the Friction Factor-Reynolds Number Relationship for Flow through Packed Beds. *Iraqi Journal of Civil Engineering* Vol. 6, No. 3, pp. 70-79.